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Review of oil water core annular flow

S. Ghosh [a], T.K. Mandal [a], G. Das [a,*], P.K. Das [b]

[a] Department of Chemical Engineering, Indian Institute of Technology, Kharagpur 721302, India
[b] Department of Mechanical Engineering, Indian Institute of Technology, Kharagpur 721302, India

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ABSTRACT

The emerging energy efficient technology in the field of high viscous oil transportation is water-lubricated transport of heavy oil, known as core annular flow or CAF. This paper provides a brief review of the past studies on oil-water core annular flows—including studies on hydrodynamics as well as stability of flow.

Contents

1. Introduction

One of the world's largest contributors of energy sector is the petroleum industry. The growing consumption of the light oil reserves has forced scientists to think of heavy oil as a suitable substitute. The major difficulty of using heavy oil is its very high viscosity. This renders its transportation almost impossible, due to the immense power requirement. Some of the conventional procedures proposed to reduce the viscosity of such oils include—provision of heating arrangements at certain intervals of the pipeline, addition of light oil, etc. However, each of the procedures has its own limitation. Hence they do not prove to be efficient enough from the point of view of energy conservation for implementation in industries. On the other hand, the water-lubricated transport of heavy oil seems to be one of the promising tools to handle the situation. In this technique, water is injected in the oil such that it flows as an annular film along the pipe wall while oil flows in the core region as shown in Fig. 1. Since the oil does not come in contact with the wall, the wall shear is comparable to the shear encountered during the flow of water only through the pipe. This reduces the pumping power and its cost drastically. This technique saves energy greatly in comparison with the other transportation process. Although this technique appears to be very attractive for heavy oil transportation, there are several problems, which need to be addressed before an economic utilization of the phenomenon can be effected. These include:

* Corresponding author. Tel.: +91 3222 283952; fax: +91 3222 255303.
E-mail address: gargi@che.iitkgp.ernet.in (G. Das).

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Nomenclature

C	constant
C_w	input water fraction
D	tube diameter (m)
f	dimensionless power reduction factor
g	gravitational acceleration (m/s^2)
HW	water holdup
J	superficial velocity of the two-phase mixture (m/s)
J_1	superficial velocity of core fluid (m/s)
J_2	superficial velocity of annular fluid (m/s)
J_{21}	drift-flux (m/s)
n	constant
Δp_{ow}	Pressure drop during core flow (Pa)
Δp_{so}	Pressure drop during oil flowing alone in the pipe (Pa)
Q	volumetric flow rate (m^3/s)
s_{io}	slip ratio
V_1	phase velocity of core fluid (m/s)
V_2	phase velocity of annular fluid (m/s)
Vi	velocity at interface (m/s)

Greek letters

Π	Pressure drop factor based on single-phase flow of annular fluid at total flowrate
ε	core volume fraction of flowing mixture
μ_1	viscosity of core liquid (Pa s)
μ_2	viscosity of annular liquid (Pa s)
ρ_1	density of core liquid (kg/m^3)
ρ_2	density of annular liquid (kg/m^3)
ρ_m	density of two-phase mixture (kg/m^3)
σ	interfacial tension (N/m)

Establishment of core annular flow to get a reduced pressure drop: Oil water core annular flow exists over a limited range of fluid velocities and water fraction for a particular diameter of the pipe. Therefore the major challenges before the researcher are to establish and maintain the flow distribution throughout the pipe length. This calls for a proper nozzle design to ensure the pattern at the start of operation and a careful adjustment of the water volume fraction to attain the desirable flow distribution.

Retention of water film at the pipe wall: It is often observed that during long hours of continuous flow the oil core touches the pipe wall and fouling occurs, thereby increasing the pressure drop drastically. Fouling depends greatly on the wetting (hydrophilic or hydrophobic) characteristics of the pipe material. Therefore selection of a proper material of construction and modification of wettability characteristics are major concerns of the problem.

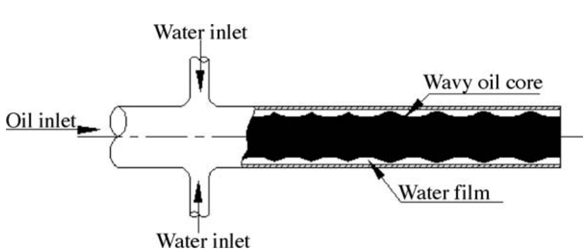


Fig. 1. Schematic of core annular in a horizontal pipe.

Stability analysis: The flow once established is required to be stable over a long period of time and a wide range of velocities. Otherwise the transportation of oil will not be feasible. Hence the range of operating conditions for which the flow is stable should be known or estimated to avoid fouling.

Some of the aspects of core annular flow are addressed in earlier reviews by Oliemans and Ooms [1] and Joseph et al. [2]. In the present work we are tried to present a comprehensive review on CAF, covering all the issues related to it. The hydrodynamics of CAF are reviewed in the first part. Nozzle design, wettability characteristics of the pipe wall, and stability of core flow is discussed subsequently. Finally, self-lubricated flow and analogies between gas liquid flow and liquid–liquid flow are analyzed in brief.

2. Modeling and experimental studies of pressure drop and holdup

One of the earliest works on CAF dates back to Clark and Shapiro [3] who patented a process of pumping viscous petroleum (μ = 0.8–1 Pa s) by injecting oil and demulsifying agents into crude oil pipeline. They reported that injection of 24% water reduced the pressure gradient by a factor of 7.8–10.5 and the optimum pressure reduction occurred when 8–10% water was injected into crude oil. However, they could not provide any idea about the prevailing flow pattern.

Russell and Charles [4] analyzed stratified flow (between wide horizontal plates) and core annular flow of two immiscible liquids with a large viscosity difference. They proposed a theoretical model which obtained the pressure drop reduction factor and power reduction factor in case of oil-water core flow. According to the model, the approximate power requirement for pumping high viscous oil (μ = 1 Pa s) can be reduced almost 500 times by establishing core annular flow. The study established core flow as an energy saving process for transporting heavy oils.

Charles et al. [5] performed experiments with oils of density 998 kg/m^3 and viscosity 0.0063, 0.0168 and 0.065 Pa s in a 0.025 m horizontal pipe. They provided a flow regime map in terms of superficial oil and water velocity and noted that core flow could not be established below a critical oil velocity for a fixed water fraction.

Hasson et al. [6] performed a systematic study of liquid–liquid annular flow by using distilled water and kerosene–perchlorethylene solution as the test liquids. They used an annular nozzle to inject the liquids into the pipeline and measured the film thickness at the wall by analyzing the trajectory of the core fluid in a horizontal pipe. The measured values as obtained from high-speed photography were in excellent agreement with the predicted trajectories for non-wavy interface as assumed in the model. Based on the observation, they proposed two mechanisms for break up of annular flow namely (a) wall-film break-up mechanism, which is strongly related to the relative wall-wetting property of the two liquids and (b) Rayleigh core break-up mechanism based on Rayleigh analysis which describes the inherent instability of a cylindrical liquid body moving as a jet.

Bentwich [7] studied two-phase Poiseuille flow of two immiscible liquids. He attempted to obtain the shape of the interface by considering interfacial tension, gravity and capillary forces. He reported that around 50% reduction of pressure was possible when the viscosity of oil was almost 20 times that of water.

Ooms et al. [8] adopted the hydrodynamic lubrication theory to analyze core annular flow of highly viscous oil and water in a horizontal pipe. They developed the model by assuming that the oil viscosity is so high that the oil–water interface can be treated as a

solid–liquid interface and, the buoyancy forces generated due to the density difference of oil and water are counterbalanced by the lubrication forces acting on the core. They presented theoretically predicted pressure loss ratio (pressure loss for core annular flow to the pressure loss for only oil flow at the same superficial oil velocity) as a function of input water fraction. The theoretical results agreed well with their experimental predictions for a 2 in. with viscous oil (μ = 2.3–3.3 Pa s) and water as the test fluids. However, for an 8 in. diameter pipe with viscous oil (μ = 1.2–2.2 Pa s) and water as the test fluids, the calculated values are differed from the measured values by more than 30%.

On the other hand, the flow of the annular liquid was noted to be turbulent by Oliemans et al. [9] in their experiments with fuel oil (μ = 3 Pa s) in a 0.05 m horizontal pipe loop with total length of 16 m. Accordingly they modified the lubrication film model by incorporating the effect of turbulence in the water annulus. The analysis required data on the waveform and wavelength for prediction of pressure gradient. The authors proposed empirical correlations to predict wavelength and water holdup.

Brauner [10] proposed an analytical model for predicting the in situ holdup and pressure drop in a horizontal pipe and obtained the power saving factor as a function of viscosity ratio. They noted that in case of laminar flow of the two liquids, the power saving factor was independent of fluid properties and for turbulent flow it increased with decrease in the differences of densities of the two phases.

Bai et al. [11] performed experiments with cylinder oil (μ = 0.6 Pa s and density 905 kg/m^3) and water, using a 0.009525 m diameter pipe in vertical up and downflow. They identified a new flow type namely bamboo waves in upflow and corkscrew waves in downflow. The schematic of the waves are shown in Fig. 2a and b. Based on the observations, they noted that for given oil flow rate there was a particular water flow rate at which the pressure drop was minimum. They also reported that the pressure drop in case of only oil flow was about 200 times

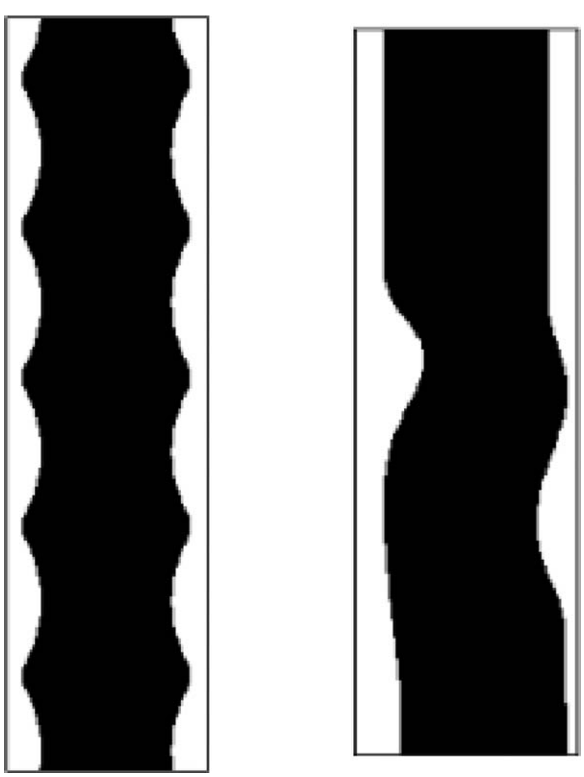


Fig. 2. (a) Schematic of bamboo wave in case of core annular downflow. (b) Schematic of corkscrew wave in case of core annular upflow.

larger than in case of lubricated flow for the same oil superficial velocity. The experimental results of flow regimes were in agreement with the predictions of previous studies based on the linear theory of stability and perfect core annular theory.

Miesen et al. [12] carried out experimental and theoretical work with fuel oil (μ = 3.9–25 Pa s) and crude oil (μ = 7–27 Pa s) as the core liquids. A 0.2% sodium silicate solution in water was used to prevent fouling of the pipe wall by oil. Two horizontal test-loops, consisting of 0.05 m inner diameter and 12 m long and 0.2 m inner diameter and 1000 m long pipes were used. A stable flow was observed when oil superficial velocity varied from 0.5 to 2 m/s and the input water fraction was in the range of 0.04–0.14. They developed a mathematical model based on two fluid Poiseuille flow and predicted the interfacial waves to have a wavelength of approximately 1–10 times the thickness of the annulus fluid.

Arney et al. [13] performed experiments with emulsified waxy crude oil (μ = 0.6 Pa s and density 985 kg/m^3) and No. 6 fuel oil (μ = 0.27 and density 989 kg/m^3) in a horizontal pipeline. They measured the pressure drop and holdup with different input flow rates and suggested an empirical correlation for holdup in terms of input water fraction. They also presented friction factor verses Reynolds number curve from a theoretical study of perfect core annular flow. The curve could predict the friction factor at higher Reynolds number but failed to predict the experimental data at low Reynolds number.

Huang et al. [14] further extended the work of Arney et al. [13] by including the effect of eccentricity on friction factor and holdup for both laminar and turbulent cases. They used the standard k–ε turbulence model to solve for the turbulent annular flow and found the friction factor to increase with eccentricity.

In 1996 Bai et al. [15] used control volume based methods to simulate core annular flow. They assumed an axisymmetric equal density wavy flow and attempted to predict wavelength, wave shape, pressure gradient and pressure distribution over the interface as a function of Reynolds number, holdup ratio, radius ratio and surface tension.

Rovinsky et al. [16] attempted an analytical prediction of the various characteristics of eccentric, laminar annular flow. They expressed velocity profiles, pressure drop reduction factor and power saving factor as a function of viscosity ratio of two phases and reported the power saving factor to increase with increase of viscosity ratio. They also proposed the optimal operating conditions in terms of the ratio of the volumetric flow rate of the two phases.

Bannwart [17] analyzed the in situ volume fraction of oil based on kinematic wave theory, where the viscosity ratio of oil to water was low. He developed a correlation for volume fraction of core in horizontal as well as vertical flow. The theoretical predictions were close to the direct holdup measurements obtained in experiments with fuel oil of density 989 kg/m^3 and μ = 2.7 Pa s in a horizontal pipe of 0.0225 m diameter.

Later Bannwart [18] proposed phenomenological models to predict the pressure drop during liquid–liquid flow through horizontal as well as vertical pipes. The analysis was an improvement over PCAF and accounted for the effect of turbulence in the annular fluid and wavy interface. It also included the effect of buoyancy for vertical system. The results showed that the largest oil flow rate require lesser amounts of water for the minimum pressure gradient. The author further suggested that the flow configuration was favored by interfacial tension, which played a major role in stabilizing the flow.

In the same year Parda and Bannwart [19] developed a theoretical model for pressure drop in vertical upward core flow. They suggested that the vertical uplift of heavy oil from the oil well could be possible by the successful application of water-lubricated flow. They demonstrated the same in a laboratory experiment

Table 1
Experimental data on core annular flow.

Author	System	Diameter (m)	Core fluid viscosity (kg/m s)	Type of core annular flow	Velocity range of core fluid (m/s)	Velocity range of water (m/s)
Charles et al. [5]	Horizontal		0.0063, 0.0168, 0.065	PCAF	0.015–0.9	0.03–1.07
Oms et al. [8]	Horizontal	0.051, 0.2	2.3, 3.2,3.3		0.97–1.1	
Oliemens et al. [9]	Horizontal	0.05	3		1	
Bai et al. [11]	Upflow, Downflow	0.0095	0.6	BW Corkscrew, Oval shaped	0.9–0.69	0.09–0.84
Miesen et al. [12]	Horizontal	0.05, 0.20	3.9–25, 7–27		0.5–2	
Arney et al. [13]	Horizontal	0.0159	0.6, 2.7	WCAF, PCAF	0.23–1.15	0.09–0.57
Bannwart [17]	Horizontal	0.0225	2.7	WCAF		
Parda and Bannwart [19]	Vertical upflow	0.0254	17.6	WCAF	0.5–1.75	0.15–0.44
Benshakaria et al. [22]	Vertical and Horizontal	0.025	4.74		0.13–0.19	0.0052–0.019
Rodriguez et al. [23]	Vertical upflow and Horizontal	0.0284	0.5	WCAF	0.007–2.5	0.04–0.5
Jana et al. [25]	Vertical upflow	0.0254	0.0012	WCAF	0.4–1.5	0.06–0.4

PCAF: perfect core annular flow, WCAF: wavy core annular flow, BW: Bamboo wave.

where the vertical uplift of oil (963 kg/m^3, μ = 17.6 Pa s) was possible using very small amount of water, through a 0.025 m pipe. The total pressure drop in case of annular flow was found to be 45 times lesser than single-phase oil flow.

Kao et al. [20] tried to simulate turbulent wavy liquid–liquid flow. They used the shear stress transport model to solve the turbulence kinetic energy and dissipation equations and found that the model prediction of pressure distribution and wavelength was better than that of original k–ω model.

Ooms and Poesio [21] studied core annular flow through a horizontal pipe. They analyzed how the buoyancy force on the core is counterbalanced in case of snake wave and bamboo waves. They found that for snake waves the buoyancy force could be counter balanced by the lubrication force but this was not possible for bamboo waves.

Bensakhria et al. [22] experimented with heavy oil (μ = 4.74 Pa s) and water in a horizontal pipeline of 12 m length and 0.025 m inner diameter. They reported a maximum of 90% reduction in pressure drop during annular flow. A small review on stability and pressure drop has also been presented in the paper.

Table 2
Correlations for pressure drop reduction factor.

Author	Equation
Russell and Charles [4]	$\frac{\Delta p_{\mathrm{ow}}}{\Delta p_{\mathrm{so}}} = \frac{\mu_1^2}{(2\mu_1 - \mu_2)\mu_2}$ μ_1 and μ_2 are the viscosities of core and annular fluid
Bentwich [7]	$f = \frac{q_1^2}{(q_1 + q_2)}$ f = non-dimensional power reduction factor q = non-dimensional volumetric flowrate
Brauner [9]	$\prod = \frac{16}{0.046}\phi_2\, Re_{2s}^{-0.8}(1+\phi)^{-1.8}$ Laminar annulus (b) $\Pi = \phi_2(1+\phi)^{-18}$ Turbulent annulus (b) where $\phi_2 = \frac{-\left(\frac{\mathrm{d}p}{\mathrm{d}x}\right)}{\left(\frac{4C}{D}\right)\left(\frac{J_2 D}{\nu_2}\right)^{n_{\mathrm{w}}}\frac{\rho_2 J_2^2}{2}}$ $\phi = \frac{J_1}{J_2}$
Parda and Bannwart [19]	$\frac{\Delta p_{\mathrm{ow}}}{\Delta l} = b\left(\frac{\rho_{\mathrm{m}} J D}{\mu_{\mathrm{m}}}\right)^{-n}\left(\frac{\rho_{\mathrm{m}} J^2}{2D(1-\varepsilon)^n}\right) - C(\rho_2 - \rho_1)g\varepsilon(1-\varepsilon)$ (Vertical upflow) b and n are adjusted from experiments
Bannwart [18]	$\frac{\Delta p_{\mathrm{ow}}}{\Delta l} = kQ^{2-n}\left(1 - \left(1 - \frac{\rho_1}{\rho_2}\right)\varepsilon\right)^{1-n}\left(1 - \left(1 - \frac{\mu_1}{\mu_2}\right)\varepsilon\right)^n$ (Horizontal flow) $\frac{\Delta p_{\mathrm{ow}}}{\Delta l} = b\left(\frac{\rho_{\mathrm{m}} J D}{\mu_{\mathrm{m}}}\right)^{-n}\left(\frac{\rho_{\mathrm{m}} J^2}{2D}\right) - C(\rho_2 - \rho_1)g\varepsilon(1-\varepsilon)$ (Vertical upflow)

Rodriguez and Bannwart [23] attempted to understand the interfacial phenomena from their experiments with crude of density 930 kg/m^3 and μ = 0.5 Pa s in a 0.0284 m vertical glass pipe. They measured the wave speed and wavelength to determine the in situ volume fraction of oil and validated the results with the data obtained from optical probe.

In a further study Rodriguez and Bannwart [24] tried to analyze the shape of the liquid–liquid wavy interface and express it in terms of pipe diameter, fluid flow rates and properties. They predicted the wavelength, amplitude and holdup ratio using the analytical model.

Jana et al. [25] observed core flow with low viscous oil (kerosene of density 787 kg/m^3 and μ = 0.0012 Pa s) in vertical upflow test rig of 0.0254 m diameter made of acrylic resin. The range of core flow in this case is very limited.

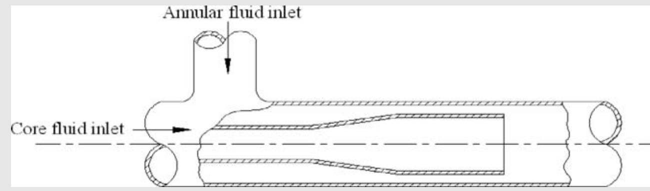
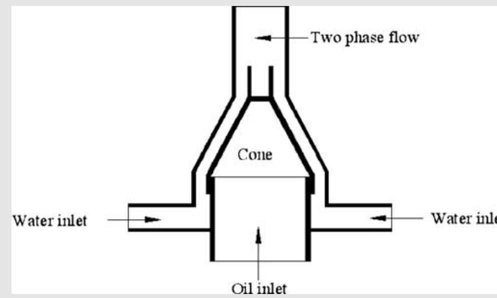
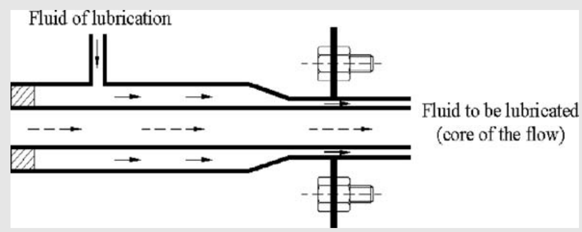
Ooms et al. [26] performed a theoretical investigation of core annular flow through a horizontal pipe. They attempted to predict out how the buoyancy force acting on the core is counterbalanced. They also calculated the development of the interfacial waves based on hydrodynamic lubrication theory.

From a study of the above literature it is evident that researchers have been taking interest in water-lubricated transport since a long time and are still exploring newer avenues. A summary of the experimental details of some of the above literature is provided in Table 1. The correlations developed for pressure drop reduction as well as the pressure gradient is given in Table 2 and the holdup correlations are presented in Table 3.

Table 3
Correlations for holdup.

Author	Equation
Olimens et al. [9]	$H_w = C_{\mathrm{w}}\,(1+(1 - C_{\mathrm{w}})^5)$
Bai et al. [11]	$\frac{H_{\mathrm{w}}}{L} = \frac{1}{\left(1 + 0.72\frac{J_1}{J_2}\right)}$ (Vertical upflow system)
Arney et al. [13]	$H_{\mathrm{w}} = C_{\mathrm{w}}[1 + 0.35(1 - C_{\mathrm{w}})]$ (Horizontal system)
Bannwart [17]	$J_1(1-\varepsilon) - s_0 J_2\varepsilon = 0$ (Horizontal system) $J_1(1-\varepsilon) - s_0 J_2\varepsilon - V_{\mathrm{ref}}F(\varepsilon) = 0$ (Vertical upflow) $V_{\mathrm{ref}} = \frac{(\rho_1 - \rho_2)g_z D^2}{16\mu_2}$ for $s_0 = 2$
Bannwart [18]	$\varepsilon = \frac{1}{1 + \frac{J_2}{J_1}\left[1 + \sqrt{1 + \frac{\mu_2 J_1}{\mu_1 J_2}}\right]}$ (Equal density laminar horizontal flow) (Infinitely viscous core, any annulus flow regime) $J_1(1-\varepsilon) - s_{\mathrm{i,0}} J_2\varepsilon - cV_{\mathrm{ref}}\varepsilon^2(1-\varepsilon)^m = 0$ (Vertical flow with infinitely viscous core) c and m are adjusted from experiments

Table 4
Different types of nozzles used for establishing CAF.

Hasson et al. [6]	
Parda and Bannwart [19]	
Bensakhria et al. [22]	

3. Nozzle-design

Since a suitable design of nozzle is essential for establishing core flow a short review on the type and design aspects of the nozzle is presented in the following section:

The nozzle used by Hasson et al. [6] was so designed that the flow path of the wall liquid is narrowed gradually. They observed that this type of configuration reduced the inlet disturbances and also found that the symmetrical position of the nozzle was more effective.

Parda and Bannwart [19] used a conical injector nozzle in their work of lifting up heavy oil from vertical wells. The nozzle inlet diameter was gradually reduced to finally match the pipe diameter and it injected water laterally to put the oil at the center of the pipe.

Bensakhria et al. [22] used an injector which introduced water in the annulus while the heavy oil passed through the core region. In Table 4 a schematic of the above-mentioned nozzles are provided.

4. Retention of water film at wall

Apart from the conventional studies on pressure drop, holdup, etc.: a few studies have also been performed to determine the effect of wetting behavior of different pipe materials and the influence of different operating parameters on the wettability characteristics. One of the earliest studies in this field was reported by Mesien et al. [12], who used 0.2% sodium silicate solution in water to prevent fouling of the pipe wall by oil. Arney et al. [27] performed several experiments with different pipe materials to study the fouling characteristics during operating conditions, emptying, shutdown and restart. They used cement lined, galvanized steel and carbon steel pipes of 0.05 m diameter for emptying tests with zuata crude (μ = 115 Pa s and density 996 kg/m^3) and water with 1% sodium silicate solution as test fluids. The operating tests were performed with fuel oil of density 900 kg/m^3 and viscosity 2 Pa s. An aqueous sodium silicate solution (1% by weight) was used as the hydrophilic agent. In all the tests they found that under the same conditions, the cement lined pipes show lesser tendency to foul than the others.

Santos et al. [28] studied the wettability characteristics of heavy oil (940 kg/m^3 and μ = 0.511 Pa s) on different pipe materials. The static contact angle was measured on different surfaces made of carbon steel, galvanized steel, stainless steel and borosilicate glass. Additives like 1% sodium metasilicate and sodium chloride solution were used to observe if their presence could influence the static angle. Preprocessing of the crude (asphaltene extraction and napthenic acid extraction) was also done in order to improve the wettability. They observed that the carbon steel and galvanized steel surfaces exhibited less water-weting behavior than glass surface and the presence of additives improved the water-wettting behavior.

Silva et al. [29] also performed several experiments to study the influence of different parameters (roughness of the surface, temperature, pH level in water and presence of salts in water) on the wetting characteristics. The pipe materials considered for the study were stainless steel, galvanized steel, commercial steel, poly vinyl chloride and enameled steel. They measured the static contact angle for oil on these surfaces before and after oxidizing with $KMnO_4$. From the experiments they observed that the oxidized surfaces were more hydrophilic than the unoxidized surfaces. They also noted that the surface roughness enhanced both the hydrophilic characteristics and the two-phase pressure drop. The pH level in water within a certain range could improve the water wettability of the surface but it was prone to problems of corrosion.

Table 5 provides a summary of the additives used by different researchers and their results.

Table 5
Effect of additives on wettability characteristic.

Author	Additives used	Pipe material used	Core fluid	Observation
Miesen et al. [12]	0.2% sodium silicate		Fuel oil (3.9–25 Pa s); Crude oil (7–27 Pa s)	Increase hydrophilic tendency
Arney et al. [13]	1% sodium silicate	Cement lined	Zuata crude	Almost oil free
	1% sodium silicate	Galvanized steel		Moderate fouling
	1% sodium silicate	Carbon steel		Complete fouling
Santos et al. [28]	(1) 1% sodium metasilicate	(1) Commercial carbon steel	(a) Crude oil (511 Pa s)	Hydrophilic
			(b) Deasphaltened oil	Hydrophilic
			(c) Deacidified oil	Hydrophilic
		(2) Galvanized steel	(a) Crude oil (511 Pa s)	Hydrophilic
			(b) Deasphaltened oil	Hydrophilic
			(c) Deacidified oil	Hydrophilic
		(3) Stainless steel	(a) Crude oil (511 Pa s)	Hydrophobic
			(b) Deasphaltened oil	Hydrophilic
			(c) Deacidified oil	Hydrophilic
		(4) Borosilicate glass	(a) Crude oil (511 Pa s)	Hydrophilic
			(b) Deasphaltened oil	Hydrophilic
			(c) Deacidified oil	Hydrophilic
	(2) 1% sodium chloride	(1) Commercial carbon steel	(a) Crude oil (511 Pa s)	Hydrophilic
			(b) Deasphaltened oil	Hydrophobic
			(c) Deacidified oil	Hydrophilic
		(2) Galvanized steel	(a) Crude oil (511 Pa s)	Hydrophobic
			(b) Deasphaltened oil	Hydrophilic
			(c) Deacidified oil	Hydrophilic
		(3) Stainless steel	(a) Crude oil (511 Pa s)	Hydrophilic
			(b) Deasphaltened oil	Hydrophilic
			(c) Deacidified oil	Hydrophilic
		(4) Borosilicate glass	(a) Crude oil (511 Pa s)	Hydrophilic
			(b) Deasphaltened oil	Hydrophilic
			(c) Deacidified oil	Hydrophilic

5. Restart procedures

Removal of high viscous oil that sticks to the pipe wall during shut down is a great challenge for the researchers. Therefore the restart methodology consists of strategic procedure to clean the pipe wall. If the pipe is not cleaned suitably then as soon as the oil pump starts it may lead to higher pressure drop and high pressure variation as described by Arney et al. [27]. They performed the restart tests for cement lined and carbon steel pipes. The experiments were done for three different down times of 24 h, 10 days and 5 days. The restart of the set up was done by increasing the water flow rate. They reported that as the down time increased, the restart became more difficult. They also noticed that for each case, the cement lined pipe fouled less than the others.

6. Stability analysis

The advantages of core annular flow can be exploited only if the flow is stable for a long time over a wide range of the operating parameters. Therefore, a stability analysis of CAF is necessary to identify the causes of instability and to determine the combination of operating and geometric parameters for which the flow is stable.

One of the causes of instability is due to the viscosity and density stratification of the two immiscible liquids. Many researchers have investigated the instability caused by the viscosity stratification for both Couttee as well as Poiseuille flow. A brief review of some important literature on this topic has been presented in this section.

Yih [30] proposed that viscosity variation could cause instability in Couttee and Poiseuille flow even for small Reynolds number and the unstable mode at times lie in the close vicinity of neutral mode for single fluid.

Hickox [31] studied the stability of Poiseuille flow of two fluids in a pipe. He reported that the flow configuration with less viscous fluid at the core and high viscous fluid at the annulus is always unstable.

Hooper and Boyd [32] investigated the causes of instability for fluids of similar density but different viscosities in an infinite region. They observed that for the fluids of same density and zero surface tension, the flow is always unstable. Based on their analysis they concluded that the surface tension helped in stabilizing the flow.

Joseph et al. [33] studied the instability characteristics of two fluids of equal density but different viscosities flowing through a pipe under a constant pressure gradient. They noted that the flow configuration with thick fluid at the core and a thin annular film is stable to long waves provided the thick fluid occupied a major portion of the pipe cross section. They also noted the stability to depend on the radius ratio. The effect of azimuthal mode number on the stability was also shown in their analysis where they found that the flow with higher azimuthal mode number was unstable.

In extension to their previous work Hooper and Boyd [34] reported another analysis on stability of Couttee flow. They considered a flow configuration where the depth of the lower but not the upper fluid. They noted that when the lower fluid had lesser kinematic viscosity in comparison with the upper fluid, the flow becomes unstable.

Preziosi et al. [35] analyzed the stability of core annular flow in horizontal pipe using linear theory. They predicted the stability of the flow in terms of the ranges of various parameters like viscosity ratio and density ratio. Their model predicted a range of Reynolds number, within which core flow is stable.

Hu and Joseph [36] extended the analysis of lubricated pipelining further by considering the stability of a hydrophobic pipeline. A finite element method was used for the analysis. They performed energy analysis of the system was performed for a small

disturbance. Based on their analysis, they identified three main causes leading to unstable flow namely interfacial shear due to viscosity differences, interfacial tension and Reynolds stress instability.

Chen et al. [37] further extended the work of Hu and Joseph [36] by including the effect of gravity on stability of flow. They also investigated the role of density difference for vertical flow and found that the flow was stabilized for heavy lubricants, where capillary instability was suppressed. For thin-layered lubrication and small density ratio, they noted certain intervals of Reynolds number in which the flow was stable.

Chen and Joseph [38] performed a non-linear analysis of core annular flow and noted two critical points, one at the upper branch and other at the lower branch of the neutral curve. They found that the flow was stable between these points. They further concluded that at the upper branch the flow became unstable due to interfacial friction and at the lower branch the flow became unstable due to capillary instability.

Chen and Joseph [39] compared different non-linear equations available in literature particularly for long waves and concluded that the capillary instability could not be properly explained by long wave theory. On the other hand, the lubrication-theory could explain the short wave instability although the stability mechanism was not well understood.

Georgiou et al. [40] performed stability analysis of vertical core flow. They investigated the effects of density and viscosity stratification on the stability for a very thin annular film where $[(R_2 - R_1)/R_1] < 10^{-2}$. Based on the analysis, they observed that for moderate surface tension, the viscosity stratification dominated the stability of flow and a flow configuration with thick fluid at the core and a thin annular film is stable under such conditions. However, in case of high surface tension, the capillary instability determined the growth rate. They also noted that the density stratification had second order effect on the stability.

Kerchman [41] studied the non-linear stability with oil in annulus. He considered a thin annulus $[(R_2 - R_1)/R_1 \ll 1]$ and the effect of pulses.

Huang and Joseph [42] analyzed stability of eccentric annular flow. They found that eccentric flow is stable in the region of stability of perfect annular flow and the neutrally stable mode is present for each eccentric case.

Hu and Patankar [43] investigated the stability with non-axisymmetric disturbances. They observed that for thin oil core, the flow is unstable for axisymmetric disturbances and concluded that axisymmetric disturbances are the most dangerous mode for a wide rage of flow parameters. They also observed the core to move in the form of corkscrew wave in agreement to an earlier observation by Bai et al. [11].

Renardy [44] studied the non-axisymmetric instability of vertical downflow. They tried to investigate whether the corkscrew and snake waves as observed in the experiments of Bai et al. [11], were bifurcated from the Perfect Core Annular Flow (PCAF). The results showed that the corkscrew waves were formed when the annular film was narrow while snakes waves were formed for a wide annulus.

Kouris and Tsamopoulos [45] analyzed the stability of two immiscible fluids flowing in a tube whose cross-section varies sinusoidally.

Bannwart [17] attempted to analyze the stability of liquid–liquid flow in a horizontal pipeline by considering the combined effect of inertial and viscous forces. Their model also predicted the shape of the liquid–liquid interface.

Wei and Rumschitzki [46] studied the effect of corrugated pipe on the linear stability of core annular flow. They found that the corrugation altered the unstable branch of Eigen values as well as the critical wave number for the system. Wei and Rumschitzki [47] further investigated the non-linear stability of core annular flow in corrugated pipes.

In recent years there have been some studies on the stability analysis of core annular flow in presence of surfactant. Wei and Rumschitzki [48] showed that the presence of surfactant increased the unstable wave numbers for core flows where the thickness of annulus was smaller than the core. Blyth et al. [49] investigated the effect of surfactant on the stability of core annular flow by normal mode linear analysis. They simulated axisymmetric perturbation using immersed interface method and found that the presence of surfactant enhances instability of flow.

Rodriguez and Bannwart [50] proposed a transition criterion for horizontal and upward vertical core flow based on the formulation of two-fluid model. They studied the effect of density, viscosity ratio and interfacial tensions on core stability and found that interfacial tension plays an important role in predicting the stable zone of core flow.

7. Self-lubricated flow

Apart from the water-lubricated transport, a highly viscous oil froth may be transported by using its own water content. This type of flow is known as self-lubricated transport. Very few studies are performed on this aspect of oil transportation due to the difficulty of performing the experiments. It was first described by Neiman [51] for the transportation of bitumen froth, produced from oil sands of Athabasca, Canada.

Joseph et al. [52] examined the self-lubricated transport of bitumen froth with different pipe diameters (0.025, 0.05 and 0.06 m) and velocity ranges (0.25–2.5 m/s). They recirculated the froth for 3–96 h. According to their study the pressure gradient for self-lubricated flow are close to the predictions of Blasius equation. The work also reports a detailed discussion on the mechanism for self-lubricated transport.

Sanders et al. [53] carried out further experiments on self-lubricated flow in a 0.025 m diameter pipe loop using Syncrude's bitumen froth (5.5 Pa s). They attempted to correlate the free water content and total water content of the froth and investigated the effect of water content on the frictional losses. They found that larger the water content, lesser is the pressure gradient and at higher velocity, the measured pressure gradient for froth containing lesser water, was very close to the value of pressure gradient predicted from Blasius equation. In addition, the holdup tests performed by this group showed that the water fraction (<10%) in this case was much less as compared to the water content required for the water-lubricated flow of crude oils.

8. Comparison of gas liquid and liquid–liquid annular flow

It is thus evident that apart from the factors influencing gas liquid flows, an additional parameter namely the wetting characteristics of the pipe wall should also be considered for liquid–liquid core flows. It influences the pressure gradient and phase distribution. Consequently, the start-up procedure and entrance condition may also affect the flow pattern. Further, while gas–liquid annular flows have been reported at very high gas velocities (20 ms^{-1}) in vertical tube (Dukler and Taitel [54]). The same type of distribution is obtained at much lower flow rates (1.79 m/s) in a 0.0254 m pipe diameter upflow by Parda and Bannwart [19] for the later case.

9. Other applications

Apart from high viscous oil transportation core annular flow also finds its application in other industries for example in food industry the transport of very viscous fluids (mayonnaise, tomato-

sauce) can be performed by the addition of a thinner immiscible fluid. In chemical and pharmaceutical industry, an immiscible low viscous fluid is used to decrease the pressure losses surrounding the high viscous liquid–liquid mixtures. Apart from these, core flow can be exploited in medical science to understand the functions of heart. Marosek et al. [55] studied the clotting behaviour in a cocurrent vertical downflow column to understand the coagulation property in a milk chamber and related this to analogous experiments with blood. Modeling of blood flow through artery has also been performed using three-layer flow by Tandon and Rana [56].

10. Conclusion

The aforementioned survey brings out the importance of core flow and studies reported on different aspects of this phenomenon like nozzle design, wettability characteristics, restart procedure, etc. A number of models to determine the pressure drop as well as holdup and the effect of geometrical (radius ratio) and operating parameters (input water fraction, flow rates of phases) have also been discussed. Several authors have observed a reduction in the pressure drop to a great extent when water lubrication is used for the transport of heavy viscous oil. Therefore, this process saves immense energy. It has been observed that core flow can be established for a particular range of water fraction and suitable additives as well as a proper choice of pipe material can reduce fouling to a great extent. Hence, it can be concluded that by proper choice of operating parameter this energy efficient process can be implemented for heavy oil transportation. So in the context of high demand of energy saving process this technique can be used as a replacement of conventional techniques of oil transportation.

Nevertheless, a close observation of the past literature reveals the grey areas which need further investigation. For example several studies are reported for horizontal and vertical upflow, not much is known about vertical downflow of oil–water systems. Moreover, not much is known about the behavior of the fluids at pipe fittings, T junction and across contraction and expansion in pipe. Some studies have been initiated by the present authors in this direction with low viscous as well as high viscous oil and water as the test fluids. Fig. 3a and b present core flow as observed by the authors in vertical downflow test rigs with two different oils.

Fig. 3. Representative figure of core annular flow in vertical downflow test rig with (a) kerosene water and (b) lubricating oil water.

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